Interdisciplinary Research Methods: Enhancing Professional Skills of Engineering Ph.D. Students

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Abstract*– This paper presents assessment of course learning outcomes achieved for a first-semester doctoral engineering course intended to promote development of the professional skills in the areas of societal context, research statistics, research ethics, technical peer review, and oral / written communication needed by engineering terminal degree graduates. Results indicate student achievement of most outcomes at or above the target benchmark levels and suggest areas for continued course improvement. Direct assessment of student learning is conducted using instructor evaluation in the form of observation and examination, and coupled with peer assessment of oral and written communication skills. The authors conclude it is feasible to achieve significant improvement in doctoral student professional skills in an inter-disciplinary classroom setting. Further, peer evaluations appear to provide most value when evaluative assessments are presented to peers as binary decisions, while formative assessments are more effective in the form of short answer queries and responses. Future work includes documenting course learning outcomes related to the intersection of public policy and engineering research, technology commercialization, intellectual property management, and the process of translating research outcomes into realized systems.

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I. INTRODUCTION

The overarching goal of the Engineering PhD program in the Kate Gleason College of Engineering (KGCOE) at Rochester Institute of Technology (RIT) is to produce terminal degree engineering graduates who are subject matter experts within and engineering discipline and have the broad, professional skills which will empower them to become leaders of inter-disciplinary research and development teams engaged in solving problems of global significance. Instead of restricting graduates to individual engineering silos (*e.g.*, mechanical, electrical, computer, industrial, chemical) the program provides students flexibility to become subject matter experts in an open-architecture environment, fostering intellectual growth along both inter-disciplinary pathways and within the bounds of conventional engineering disciplines. With this approach, the program seeks to produce world-class researchers who can capitalize on the most promising discoveries and innovations, regardless of their origin within the engineering field, to develop inter-disciplinary solutions for real-world challenges.

The term "inter-disciplinary" is used in a manner consistent with both the United States' National Science Foundation (NSF) and the National Academy of Engineering (NAE). NSF refers to and uses the NAE definition [1]:

> *"Interdisciplinary research is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice."*

Our aspiration for the Engineering PhD program is to educate the next generation of engineering leaders in a manner that will allow them to tackle some of the most daunting and complex problems facing our global society. In the past, dramatically complex problems such as *"landing a man on the moon and returning him safely to the earth"* [2] required the full resources of an entire nation to solve. Today, we face global challenges in Transportation, Energy, Communication, and Healthcare (T/E/C/H) which demand highly trained engineers with deep disciplinary skills and a thorough contextual understanding for their research efforts.

Our approach is to produce nimble professionals who can innovatively solve problems of global significance whose solutions are beyond the scope of a single discipline. We have chosen to create a terminal degree in engineering whose participants will align with one of four application domains (T/E/C/H). These application domains provide contextual elements regarding national and global priorities, fostering collaboration among faculty and students in different engineering disciplines. These contextual elements should provide graduates a competitive advantage in industry and academia.

We aspire that the Engineering PhD program will prove to be a role model for the way in which other programs at RIT structure terminal degree offerings in their disciplines. Traditional disciplinary doctoral degrees in engineering (mechanical, electrical, industrial, chemical, civil, *etc.*) provide tremendous value to society. The intent of the RIT Engineering PhD is to provide a strong foundation in traditional disciplinary studies complemented by a more thorough contextual understanding than is common in most engineering doctoral programs today.

The solutions of societal and global grand challenges lie at the intersection of many core disciplines. Students having exposure to fields outside their core training will be more able to interact and work with others than a person with only core training. The need to balance depth of knowledge with the breadth provided by contextual understanding will become even more important in future decades. In his essay, "Preparing Stewards of the Discipline", Chris M. Gold [3] of

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the Carnegie Foundation for the Advancement of Teaching, describes the role of doctoral degree recipients as the "stewards of the discipline" and he states that

> *"...Every scholar and steward must strike a balance between mastering breadth and depth in the discipline. Typically, doctoral students learn a small area in great depth, but this deep understanding must be place in context. Once students understand the historical context of the field -- how and when important ideas, questions, perspectives, and controversies arose or fell (or were overturned) -- then they can grasp the span and sweep of the field and locate themselves and their work in the disciplinary landscape ..."*

The RIT Engineering Ph.D. program is designed to include this contextual understanding of not only the engineering discipline, but also the societal context of the problem space in which the student will work. Traditional doctoral engineering curricula do not usually include such professional skills development as part of the course work, but rely upon individual faculty advisors to provide those skills through mentoring. Research faculty members may lack the background needed to provide students with formal training in learning outcomes assessment, technical communication, public policy, professional ethics and entrepreneurship – which have been identified short-comings in traditional engineering doctoral education. These shortcomings potentially reduce the broader impact of their research outcomes. Holly Hillberg, (now former) V.P. of Research and Development at Ortho Clinical Diagnostics, stated [4] that

> *"Graduates of these traditional disciplinary doctoral programs advance knowledge and provide value to society. Unfortunately, graduates of such programs face impediments to success as new PhD employees resulting from an inability to translate their very deep knowledge and skill set obtained during their PhD work into the broader applications of that research. As a result, traditionally trained PhD students can find it difficult to work with PhDs from other disciplines, which is unfortunate because their composite skills are necessary to deliver a healthcare product. The contextual elements of the [RIT Engineering PhD] program afforded by its interdisciplinary nature will give its PhD graduates a competitive advantage in the workplace."*

The program is designed for students to complete rigorous work in traditional disciplines complemented by interdisciplinary graduate level coursework and research. The resulting graduate from the "Arrow-Targeted" Ph.D. program illustrated in Fig 1 will be prepared to better handle interdisciplinary research challenges than those who are formally trained exclusively in narrow core disciplines.

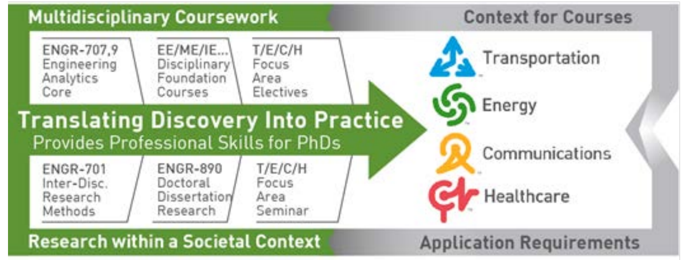

Fig. 1 The arrow-targeted curriculum includes focus on the t-shaped professional skills needs by doctoral engineers, incorporating industry and societal feedback loops to inform the content of doctoral course work and context of research investigations.

Fig 1 illustrates four traditional curricular elements found in STEM doctoral programs (analytics core and disciplinary foundation coursework, elective coursework, and doctoral research) complemented by three novel curricular elements (Inter-disciplinary Research Methods, T/E/C/H focus area seminar, and Translating Discovery into Practice) central to the RIT Engineering PhD program. The focus of this paper is on the "ENGR-701 Inter-disciplinary Research Methods" course typically taken by students in the fall semester of their first year in the doctoral program.

II. The Engineering PhD Program at RIT

A. *Program Mission, Philosophy and Curricular Structure*

The mission of the Engineering PhD is to produce nimble professionals who can innovatively and collaboratively solve problems of global significance whose solution are beyond the scope of a single discipline.

The philosophy of the program is to provide technology-based research and educational programs for personal and professional development through the rigorous advancement of knowledge in areas relevant to emerging technologies and social conditions, and developing the talented engineering workforce to tackle 21st century problems.

The structure of the Engineering PhD program curriculum [5] illustrated in Fig 2 is guided by two principles.

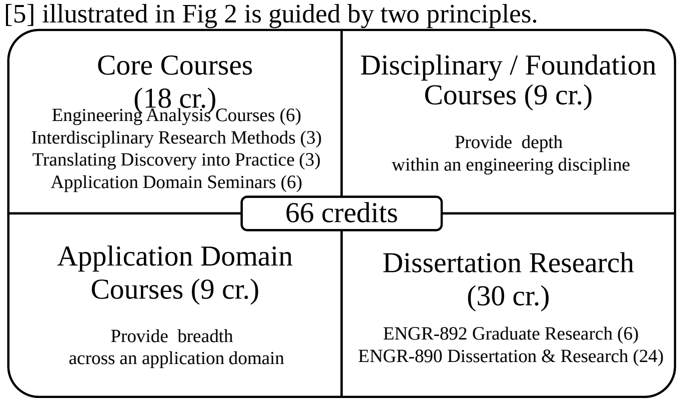

Fig. 2 The Engineering PhD program at RIT consists of 66 semester credits composed of course work and independent research to achieve technical depth while developing t-shaped professional skills.

First, the curriculum must be flexible to provide societally or industrially inspired training and education through disciplinary courses, research mentorship and engineering focus area seminars. Second, the curriculum must ensure that graduates have disciplinary-rooted technical strength to conduct and complete independent and novel research that is by nature collaborative and inter-disciplinary.

The core courses provide a common mathematical foundation for all students in the PhD program and focus on the development of the professional skills required for doctoral researchers which span disciplinary boundaries. The foundation elective courses drive students to achieve technical depth in their discipline, while the application domain electives foster development of broad technical skills drawn from graduate courses available throughout the college of engineering. As with most doctoral programs, dissertation research is the integrative element which brings everything together. The curriculum complements disciplinary depth of study with broad understanding of an application domain.

B. Program Goals and Outcomes

The Engineering PhD program is designed to achieve three top-level goals for its graduates, and several program-level learning outcomes associated with each goal:

1. **Conduct Impactful Research:** Produce graduates able to conduct independent inter-disciplinary research to address compelling problems of national and global significance in four application domains of Transportation, Energy, Communications and Healthcare.
   a. **Research:** Design, conduct, and present independent, advanced inter-disciplinary research.
   b. **Ethics:** Demonstrate knowledge of the ethical and responsible conduct of research.
   c. **Communication:** Demonstrate effective communicative skills across a variety of teaching, research, and training situations.
2. **Demonstrate Technical Strength:** Produce graduates who will exhibit a strong foundation in engineering knowledge, as subject matter experts within a traditional discipline of engineering, to pursue careers in engineering research or education.
   a. **Mathematics & Engineering Analysis:** Demonstrate an advanced technical level of engineering analysis capabilities at post-baccalaureate level.
   b. **Disciplinary Foundation:** Demonstrate an advanced technical level of engineering expertise in one engineering discipline at the post-baccalaureate level.
   c. **Application Domain Expertise:** Demonstrate an advanced technical level of engineering expertise in one application domain at the post-baccalaureate level.
3. **Translate Discovery into Practice:** Produce graduates having essential professional skills necessary to translate deep technical knowledge and scientific discoveries into socially relevant engineering solutions and practical application through careers in academe and industry.
   a. **Societal Context:** Demonstrate an understanding of the interplay between policy, societal context, and engineering research.
   b. **Commercialization:** Demonstrate an understanding of paths to technology commercialization and product development from basic and applied research.
   c. **Realization:** Demonstrate an understanding of engineering product evolution and implementation in T/E/CH application domains.

C. Program Level Curriculum Map

The Engineering PhD program components are designed to contribute to the achievement and assessment of the Program-level Learning Outcomes (PLOs) in an integrated fashion as illustrated in Table I.

TABLE I

CURRICULUM MAP, ILLUSTRATING RELATIONSHIP BETWEEN COURSES AND EXPERIENCES AND ACHIEVEMENT OF PROGRAM-LEVEL LEARNING OUTCOMES.

Courses and Experiences	Conduct Impactful Research			Demonstrate Technical Strength			Translate Discovery Into Practice		
	Research	Ethics	Commun-ication	Mathematics & Engineering Analysis	Disciplinary Foundation	Application Domain Expertise	Societal Context	Commercial-ization	Realization
ENGR-701 Interdisciplinary Research Methods	R, A	R, A	I, A		R	R	R, A		
ENGR-702 Translating Discovery into Practice	R	M	R, A		R	R	R, A	R, A	R, A
ENGR-707 Engineering Analysis	R	M, A		M, A	R	R			
ENGR-709 Advanced Engineering Math				M, A	R	R			
ENGR-795 Doctoral Seminar			M, A				R	R	R

3 Disciplinary Foundation Courses					M, A				
3 T/E/C/H Courses						M, A			
ENGR-890 Dissertation	M, A	M, A	M, A	M, A	M, A	M, A	M, A	M, A	M, A
2 Public Outreach Articles or Events			M				M		
2 Peer Reviewed Publications			M, A					M	
Key: "I"=introduced; "R"=reinforced and opportunity to practice; "M"=mastery at the senior or exit level; "A"=assessment evidence collected									

III. Inter-disciplinary Research Methods

A. *Course Philosophy and Structure*

Two courses, Inter-disciplinary Research Methods (IRM) and Translating Discovery into Practice (TDP), are the core professional skills development courses in the Engineering Ph.D. program. These courses are composed of several learning modules as illustrated in Fig 3.

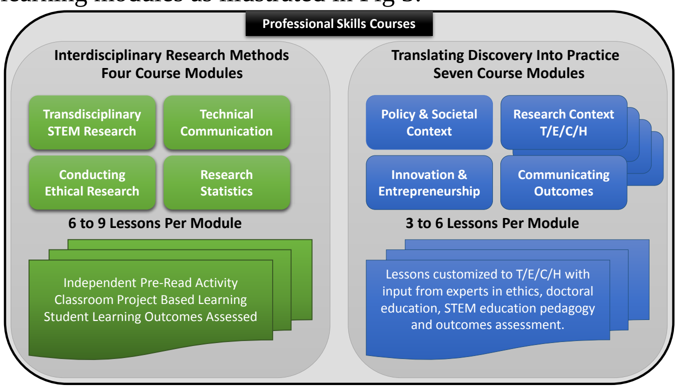

Fig. 3 Professional Skills Development Core Courses Structure.

The IRM course emphasizes collaboration in modern research environment and consists of four modules having at least one formative assessment.

Module 1. Enabling Trans-disciplinary STEM Research. This module introduces students to the concepts of inter-disciplinary (*e.g.* across engineering disciplines) and trans-disciplinary (*e.g.* across basic science and engineering) research. [1] Students learn about context for research through review of national priorities in a variety of societal needs [6-11]. Students integrate hypothesis-driven scientific research using the scientific method with engineering research using the engineering problem solving and design methods.

Module 2. Research Statistics. This module begins with a review of descriptive and inferential statistics for engineering research. Topics include sample size and power calculations, hypothesis testing, confidence intervals, analysis of variance, linear and logistic regression, and design of experiments. The NSF funded open-source textbook by Lane *et al* is used throughout this module [12]. Examples of statistical rigor and a critical assessment of appropriate statistical methods are emphasized with respect to engineering applications.

Module 3. Conducting Ethical Research. Classroom seminars on "diversity and cooperation", "values in science" and "deception, self-deception, and self-regulation in scientific research" have been adopted from a course supported by the NSF for PhD students in science, engineering, and philosophy of science [13]. Students participate in moderated discussion groups about ethics case studies [14] related to (a) responsible conduct of research, (b) responsibility in the context of the engineering professions, (c) authorship and plagiarism, (d) basic criteria for ethical decision making [13, 15], and (e) professional standards and code of ethics relevant to their discipline.

Module 4. Technical Communication. This module focuses on written and oral [16] technical communication skills, through individual case studies related to the completion of a mock qualifying examination. Skills demonstrated include a thorough written review and critique of a technical article, along with an oral presentation of the review and suggestions for future work. Students develop skills related to reviewing [17] and annotating technical papers, conducting a literature search and proper citation. Students learn proper use of library and internet resources and research database tools, conduct reviews of research articles and use a rubric to conduct peer assessments.

B. *Course Learning Outcomes*

Four Course Learning Outcomes (CLOs) are associated with the Inter-disciplinary Research Methods course, one for each of the four course modules:

CLO 1. Demonstrate an ability to design, conduct, and present independent, advanced inter-disciplinary research.

CLO 2. Demonstrate effective communication skills across a variety of teaching, research, and training situations.

CLO 3. Demonstrate an ability to scope research and manage a research project by creating a detailed plan of study.

CLO 4. Demonstrate an ability to conduct ethical research through an understanding of ethical responsibilities.

C. *Course Level Assessment Plan*

The assessment methods and instruments associated with each of the four Course Learning Outcomes (CLOs) are presented in Table II and reflect the Program-Level Learning

Outcomes (PLOs) assigned to the Inter-disciplinary Research Methods Course in Table I. The course assumes that students have had little prior formal exposure to graduate level technical writing in English, so this CLO is considered introductory, and is accompanied by assessment, “I, A”, as shown in Table I. Conversely, the course assumes students have had prior formal training in conducting research, undergraduate statistics, professional ethics, and social context, also accompanied by assessment, shown as “R, A” in Table I. While it is intended that the course reinforce each students’ disciplinary foundation and their interest in market-driven applied research, the course does not include assessment of these topics, as reflected by the “R” entries in Table I.

TABLE II
INTER-DISCIPLINARY RESEARCH METHODS
COURSE LEARNING OUTCOMES AND ASSESSMENT METHODS

Course Learning Outcome	Assessment Method
CLO 1. Demonstrate an ability to design, conduct, and present independent, advanced inter-disciplinary research.	Module 1: Trans-disciplinary Research Examination.
	Module 2: Research Statistics Examination.
CLO 2. Demonstrate effective communication skills across a variety of teaching, research, and training situations	Module 4: Mock Qualifying Exam Term Paper and Presentation Assessment.
CLO 3. Demonstrate an ability to scope research and manage a research project by creating a detailed plan of study.	Module 4: Mock Qualifying Exam Term Paper Assessment.
CLO 4. Demonstrate an ability to conduct ethical research through an understanding of ethical responsibilities.	Module 3: *Research Ethics* On-line training module, examination and completion certificate.

The IRM class meets for one class hour, three days per week during the semester. Each lecture hour is used to introduce a new topic to students, as shown in Table III, based on information from published sources. Students are encouraged to rely upon published articles and research findings not only for their research, but for all aspects of their homework assignments in the class.

TABLE III
INTER-DISCIPLINARY RESEARCH METHODS
LESSON AND TOPIC SCHEDULE, WITH REFERENCES

Hr.	Topics Covered During Lecture
	Module 1: Transdisciplinary STEM Research
1	Goals and objectives of the Engineering PhD Program
2	Enabling Trans-disciplinary Research
3	Scientific Research *vs.* Engineering Research
4	Research Proposals and Funding
5	Introduce the Mock Qualifying Exam (MQE) Term Paper
6	Trans-disciplinary Research Examination
	Module 2: Research Statistics
7	Introduction to Distributions
8	Describing Data
9	Estimation
10	Logic of Hypothesis Testing
11	Testing Means
12	Power
13	Regression
14	ANOVA – Analysis of Variance
15	Research Statistics Examination
16	Critically Evaluating Work of Others
17	Using the University Writing Commons
	Module 3: Conducting Ethical Research
18	A framework for ethical decision making.
19	Case Study - "Student Publishes"
20	Case Study - "Credit for Research Data"
21	Authorship, Plagiarism & Copyright; Citing Sources
22	Values - “Ethical Responsibility in Engineering”
23	Case Study - "Fraud in Engineering &Scientific Research”
24	Overview - Responsible Conduct of Research
25	Q & A Session with students about upcoming MQE Exam
26	Engineering Research Ethics Examination
	Module 4: Technical Communication
27	Preparing an Outline for your MQE Critical review paper
28	Revising & Editing your MQE Term Paper
29	Preparing an effective MQE Presentation
30-31	Using The RIT Libraries for your Research
32	Schedule and Logistics Planning for end of semester
33	Final steps for your MQE Term Paper
34-35	Research Data Management
36-45	MQE Oral Exam Student presentations, 18 minutes each

IV. RESULTS

A. *Assessment of Trans-disciplinary Research CLO*

Upon conclusion of the first module of the course, students completed a 25 question multiple-choice examination which focused on comprehension of the reading assignments and extension of the classroom discussion on the subject matter. Each question included five potential answers, from which students were instructed to select one or more correct answers. The 25 questions used to assess this CLO were:

Q1. Please select all of the following items that were identified in the NSF Science and Engineering Indicators Overview document as being essential elements of growing a knowledge intensive economy.

Q2. Which of the following best describes the percent change that Knowledge and Technology Intensive (KTI) industries within developed economies contributed to the world's Gross Domestic Product (GDP) from 1997 to 2012?

Q3. Which of the following regions or countries exhibited the largest increase in High Tech Manufacturing industries from 1997 to 2012?

Q4. Which ONE of the following regions or countries experienced the biggest increase in R&D expenditures as a percentage of GLOBAL R&D expenditures between 1996 and 2011?

Q5. Which of the following countries or regions experienced the largest increase in researchers employed as a percentage of total employment between 1995 and 2011?

Q6. Which of the following countries / regions had the highest enrollment of international graduate students coming to this country / region as of 2010?

Q7. Please select all of the items from the list below which were identified as top level goals in the ARISE II report.
Q8. Through Q11. Which one of the following scenarios is most well aligned with one of the ARISE II recommendations?
Q12. In the "Craft of Research" the authors suggest several reasons for writing documents describing the findings of research efforts, focused inwardly on the researcher, as opposed to an external audience. Please select all of the reasons suggested by the authors from the following list.
Q13. In the "Craft of Research" the authors suggest several roles for an author to take on in an effort to make write a compelling article that readers are eager to read. Please select all of the roles suggested in the "Craft of Research" as being good roles for writers to take on.
Q14. In the "Craft of Research" the authors suggest several objectives that various readers may have when they are reading a research article. Please select all of the objectives suggested in the "Craft of Research" as being typical objectives that readers have when reading research articles.
Q15. Which of the following items best describes the term "course withdrawal" as defined in the KGCOE graduate Handbook?
Q16. Which of the items does not accurately describe Kate Gleason, the namesake of the KGCOE?
Q17. Which of the items does not describe a capability of the RIT Student Information System (SIS)?
Q18. Which of the answer best describes the fall term grade point average of a student who takes a 3-credit course for an "A" and a 3-credit course for a "B" and a 1-credit course for an "A"?
Q19. Which of following responses describes a professional society that does not currently have an RIT KGCOE student section?
Q20. Which of the items best describes the sequence in which the PhD exams must be completed?
Q21. Which of the items best describes the research purpose of the KGCOE Engineering PhD program?
Q22. Which of the items best describes the reason that the Transportation, Energy, Communications and Healthcare Domains were selected as unifying themes for the KGCOE Engineering PhD program?
Q23. Please select all of the following items that accurately describe one or more responsibilities of various branches of the US Federal (National Level) government.
Q24. Please select the answer which best describe a definition of "basic research" as used by the federal government.
Q25. Which answer best describes the time, in the overall procurement process, when an individual faculty member prepares a proposal and submits it to a funding agency?

Results of the trans-disciplinary research CLO examination for fall semester 2016, taken by 21 first year engineering doctoral students, are presented in Fig 4. The program assessment plan benchmark target for achievement of CLOs has been set at 70% positive response rate across the KGCOE. The mean score for this examination was 88% with a low score of 71% and a high score of 100% and standard deviation of 6.8% and standard error of the mean of ±1.5%. Inspection of student performance on individual question provides insights for course improvement. Questions 1 and 5 exhibited correct response rates of 62 ± 1.5%, suggesting that additional classroom time or discussion should be spent regarding the attributes of knowledge and technology intensive (Q1) economies and the U.S. federal process by which faculty members seek financial support for their research (Q25).

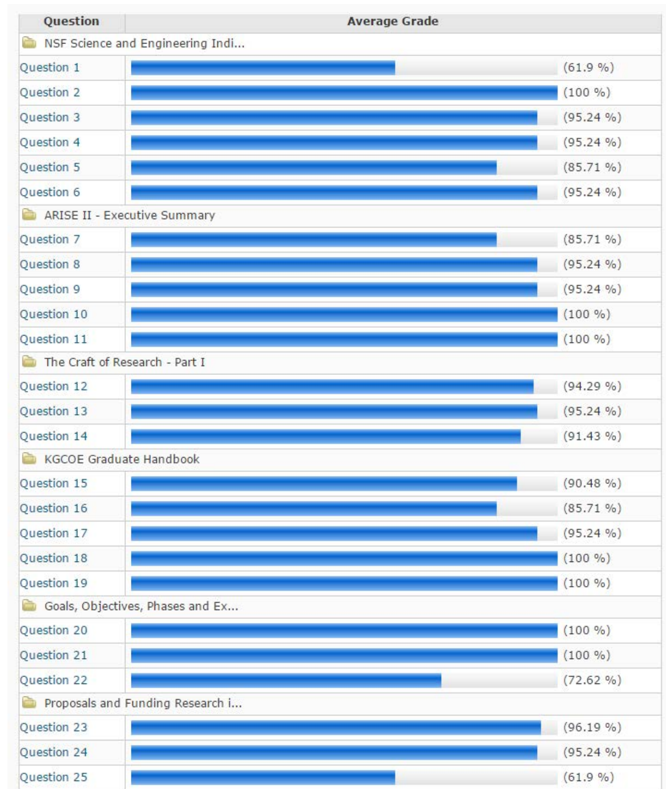

Fig. 4 Results of the Trans-disciplinary Research Examination for the Fall 2016 offering of Inter-disciplinary Research Methods, N=21.

B. Assessment of Research Statistics CLO

Upon conclusion of the research statistics module, students completed an examination which required use and interpretation of an actual research publication data set [18] provided to students as part of the exam handout. Problem 1 consisted of five multiple choice questions focused on understanding of statistical concepts and terminology:

T1 Which one of the following responses does not describe Figures 1 and 2?
T2 Based on Figures 1 and 2, which response is the best estimate for the Median Puff Volume of Subject 9?

T3 Based on Figures 1 and 2, which response is the best estimate for the Mean Puff Volume of Subject 10?

T4 Based on Figures 1 and 2, which response is the best estimate for the range of the 95% Confidence Interval of Puff Volume for Subject 19?

T5 Based on Figures 1 and 2, which response is the best estimate for the 75th percentile Puff Volume of Subject 16?

Problem 2 consisted of five short single-step computation problems to assess students' ability to properly apply knowledge:

P2.1 Compute the point estimates for the standard error of the mean of Puff Volume for Subjects 6 and 12 using the data presented in Table 1.

P2.2 Conduct a *t*-test to evaluate whether there is statistically significant difference in the mean Puff Volume between Subjects 2 and 16 at the 99% confidence level using the data presented in Table 1.

P2.3 Compute the probability of a Type I error when conducting a *t*-test to evaluate whether there is statistically significant difference in the mean Puff Volume between Subjects 15 and 17 using the data presented in Table 1.

P2.4 Fit a polynomial using ordinary least squares, assuming X is the independent variable and Y is the dependent variable, using the data presented in Table 2. Show all work. State and justify your assumptions and decisions.

P2.5 Compute the regression correlation coefficient, R^2, for the polynomial regression that you completed in the previous step. Show all work. State and justify your assumptions and decisions.

Problems 3 and 4 required students to make assumptions and conduct multiple computations to arrive at a statistically relevant conclusion:

P3. Calculate the power of H_A for comparison between means of Subject 20 and Subject 8. State all assumptions. Show all work.

P4. Conduct a between subjects ANOVA for Puff Volume, for all 20 subjects. State all assumptions. Show all work.

Results of the research statistics examination are presented in Fig 5, demonstrating achievement of the introductory research statistics CLO.

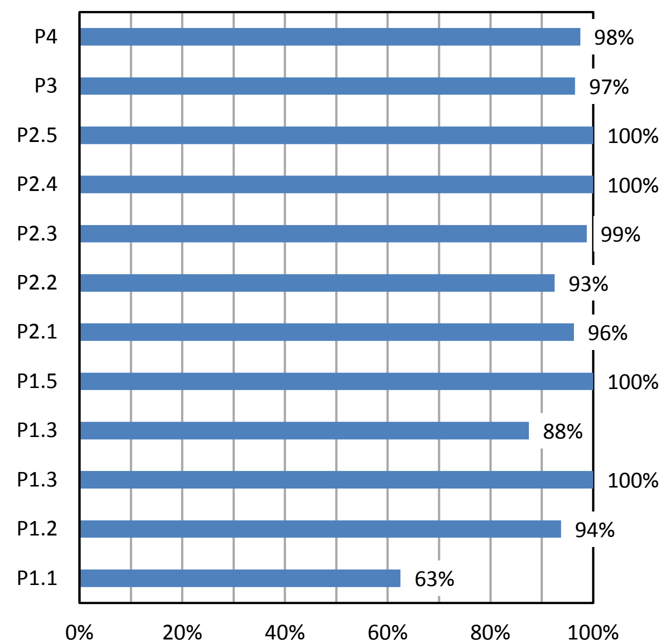

Fig. 5 Results of the Research Statistics Examination for the Fall 2016 offering of Inter-disciplinary Research Methods, N=21.

Upon review of the low performance achieved on P1.1, it was decided that the phrasing of the question prompt and the responses offered could be confusing, particularly to non-native English language readers. Care will be taken to avoid such phrasing and observe if the response improves in the next course offering, or determine if additional course time needs to be spent on statistics terminology.

C. *Assessment of Research Ethics CLO*

Upon completion of the classroom activities and reading assignments for the Research Ethics module, each student was tasked with completing the Collaborative Institutional Training Initiative (CITI) program (https://www.citiprogram.org/) for Responsible Conduct of Research (RCR) for engineers. The examination consisted of 9 topics, with 5 multiple choice questions per topic. The topic areas included:

T1 Research Involving Human Subjects.

T2 Plagiarism.

T3 Authorship.

T4 Collaborative Research.

T5 Conflicts of Interest.

T6 Data Management.

T7 Mentoring.

T8 Peer Review.

T9 Research Misconduct.

Results of the research ethics examination for fall semester 2016 are presented in Fig 6.

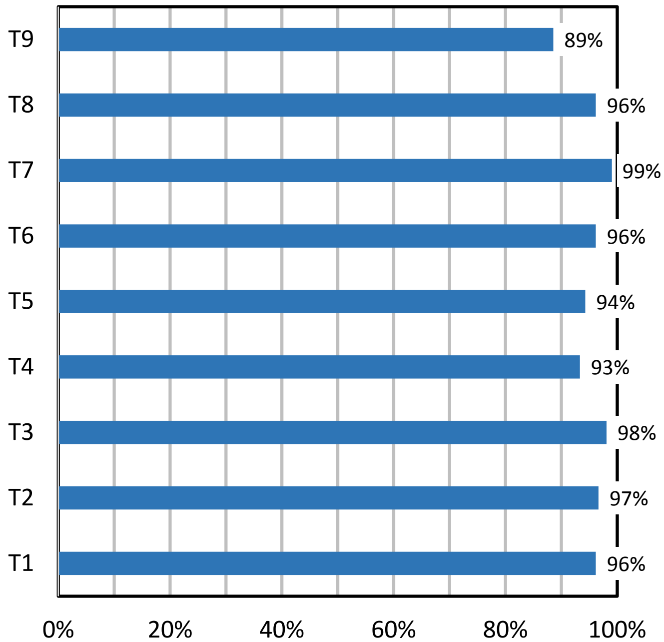

Fig. 6 Results of the Research Ethics Examination (first attempt) for the Fall 2016 offering of Inter-disciplinary Research Methods, N=21.

On average, the cohort of students demonstrated performance above the 70% benchmark on every topic (for their first attempt at the exam) as illustrated in Fig 6, demonstrating achievement of the Research Ethics CLO. In addition, every student demonstrated a composite score across the nine topics above 70%. One student achieved a score of 60% on Topics 6 (Data Management) and 8 (Peer Review). One student achieved a score of only 20% on Topic 9 (Research Misconduct) on their first attempt, but a perfect score of 100% following discussion and re-examination. In that particular case, based on review with the student, the instructor attributed the low score to English language comprehension issues, as opposed to subject matter misunderstanding.

D. Assessment of Technical Communication CLO

Each student was required to prepare a 15 page written term paper, and an 18 minute oral presentation to the class. Each class member was provided with an oral presentation peer-review rubric, and asked to assign a score between 0 (Unsatisfactory) and 4 (Outstanding) on each of several presentation attributes. Among the oral communication attributes evaluated by peer review are:

C1. Literature Review & Citation Management
C2. Articulation and Enunciation
C3. Auditory Volume or Sign Clarity
C4. Communicate Effectively for Understanding
C5. Presentation Time Management
C6. Room and Audience Management

Results of the peer "oral communication" assessment for fall semester 2016 are presented in Fig 7. Each student was asked to conduct peer evaluations of every other student in the class, except for the day on which they made presentations, resulting in 177 data points for each of the six attributes reported in Fig 7. Students scored each attribute on a sale from 0 to 5, and were asked to provide 1 or 2 sentences of constructive criticism to their peers on each attribute. Students were provided with a rubric to be used in evaluating the numerical score for each attribute. The average responses were converted to a percentage scale in order to be consistent with previously presented results.

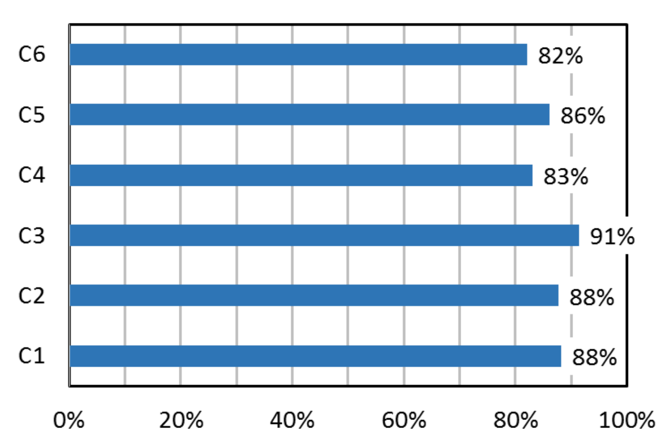

Fig. 7 Results of oral communication round-robin peer assessment of presentations for the Fall 2016 offering of Inter-disciplinary Research Methods, N=177 per response attribute.

The round-robin peer reviews of student oral presentations suggests that all six attributes exhibit performance above the 70% benchmark as illustrated in Figure 7. Unfortunately, it was observed that many students indicated a high numerical value for certain attributes, even when their short answer responses to the same attribute prompt indicated areas of significant improvement needed. Upon comparing the written feedback comments (which often resonated with the faculty members' observations regarding the presentations) against the scoring rubric provided by the instructor to the students, it was obvious the peer evaluations were consistently inflated relative to the score suggested by the instructor-provided rubric. The authors conclude from this observation that there is significant value in requiring students to provide a written response rather than just a numerical assessment.

In addition to the round-robin peer evaluations of classroom presentations, each student was required to conduct a peer review of one other student's written term paper. Observing the ``grade inflation'' tendency of student numerical grading from the oral presentation reviews, the instructor modified the feedback form employed for the peer evaluations of the written term papers. The review consisted of (a) a series of six "Yes/No" questions, (b) one dozen short response questions, and (c) an editorial "mark-up" of their peer's draft term paper. This generated a wealth of feedback between peers, across disciplinary boundaries, and between native and non-native English language speakers. The six "Yes/No" questions for the written term paper assessment were:

W1. Does the term paper convey the meaning of the student author?
W2. Is the paper written well enough for the faculty reviewer to evaluate the technical content?
W3. Does the abstract describe the paper?
W4. Does the introduction adequately explain the problem and the research framework?
W5. Are the remaining sections clear, and do they follow in a logical order?
W6. Does student demonstrate the ability to critically evaluate work done by others?

Results of the peer "written communication" assessment for fall semester 2016 are presented in Fig 8. These responses indicate the percentage of peers responding "Yes" to each question.

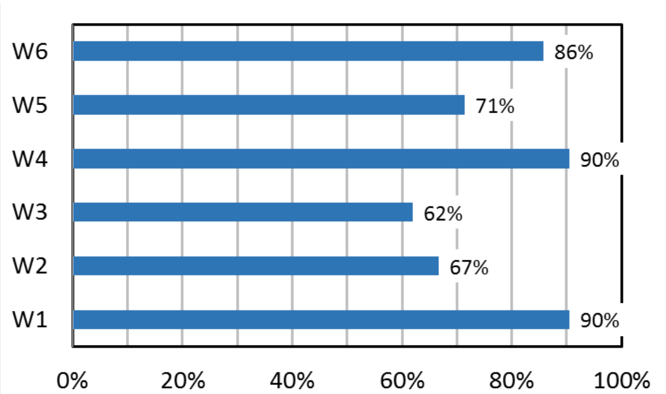

Fig. 8 Results of written communication peer assessment of term papers for the Fall 2016 offering of Inter-disciplinary Research Methods, N=21.

The one-to-one peer reviews of student written term papers suggests that three of six attributes exhibit performance well above the 70% benchmark as illustrated in Figure 8. The attribute W5, regarding the logical outline of the paper, is marginally acceptable at 71% average score. The responses to W2 (technical content) and W3 (abstract) do not meet the benchmark, suggesting that this be an area for additional focus in the next offering of the course. In contrast to the round-robin oral presentation peer reviews, it was observed that most students' "Yes/No" responses were self-consistent with their short answer responses to the same attribute prompt. This observation suggests students may either be *(i)* better able, or *(ii)* more willing, to make accurate critical peer-assessments when presented with binary choices and are more likely to inflate numerical scores when given an opportunity to evaluate attributes on a numerical scale.

V. Conclusions

It is feasible to achieve significant improvement in engineering doctoral student professional skills in an inter-disciplinary classroom setting. Course learning outcomes associated with four modules were assessed: "Enabling Trans-disciplinary STEM Research", "Research Statistics", "Conducting Ethical Research", and "Technical Communication". Assessment results indicate student achievement of most outcomes at or above the 70% target benchmark level. Specific areas for course improvement include spending more classroom time on (1) the attributes of knowledge and technology intensive economies, (2) the U.S. federal process by which faculty members seek financial support for research, (3) technical writing for understanding and developing effective outlines, and (4) writing effective abstracts of technical articles. Students demonstrated a high degree of understanding related to ethical and professional responsibilities in the conduct of research. The formulation of word problems and writing prompts may pose a particular challenge to non-native English speakers, particularly when addressing societal norms and potentially conflicting statements employed in case studies. Evaluative assessments appear to provide most accurate feedback when questions are presented to peers as binary decisions, while formative assessments are more effective in the form of short answer queries and responses. Additional course work is needed for engineering doctoral students to develop effective professional skills related to the intersection of public policy and engineering research, technology commercialization, intellectual property management, and the process of translating research outcomes into realized systems.

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